Spin orientation of two-dimensional electron gas under intraband optical pumping

S.A. Tarasenko and E.L. Ivchenko
A.F. Ioffe Physico-Technical Institute, Russian Academy of Sciences, 194021 St. Petersburg, Russia

The theory of spin orientation of two-dimensional (2D) electron gas has been developed for intrasubband indirect optical transitions. The monopolar optical orientation of electrons in the conduction band is caused by the indirect scattering with virtual intermediate states in the valence band and allowance for selection rules for interband transitions. The considered mechanism of optical orientation is shown to be in an inherent relation with the special Elliot-Yafet mechanism of electron spin relaxation induced by virtual interband scattering.

I. INTRODUCTION

In recent years spin-dependent phenomena in low-dimensional structures attract a great attention. One of the problems of common interest is a possibility and methods of the spin polarization in systems with a two-dimensional electron gas. The conventional way to achieve the spin polarization experimentally is the optical orientation of electron spins [1]. Under optical excitation with the circularly polarized light the direct transitions from the valence to the conduction band are allowed only if the angular momentum is changed by ± 1. These selection rules lead to the spin orientation of optically excited electrons, with the sign and the degree of polarization depending on the light helicity.

Up to now the theoretical consideration of the optical spin orientation was focused on direct interband transitions [1] and, partially, on direct intersubband transitions in the complicated valence band Γ_8 of a zinc-blende lattice semiconductor [2]. Here we report for the first time a theory of optical spin orientation under the indirect intrasubband excitation of electron gas by circularly polarized light and give an estimate of the spin generation rate. Note that the "monopolar" optical orientation under consideration can serve as a model of spin injection because the only type of carriers, electrons, is involved.

In addition, the short-range Elliot-Yafet mechanism of electron spin relaxation considered previously only for bulk semiconductors ([1], ch. 3) is extended to quantum-well structures. This spin-relaxation mechanism is shown to be governed by the same interband matrix elements of the electron-phonon or electron-defect interaction as those which govern the indirect intrasubband optical orientation.

II. MONOPOLAR OPTICAL ORIENTATION OF ELECTRON GAS

The light absorption under intrasubband excitation in quantum wells (Drude-like absorption) is possible only if it is assisted by a phonon or a static imperfection in order to satisfy simultaneously both the energy and momentum conservation laws. Theoretically, these indirect optical transitions with initial and final states in the same conduction subband n are described by second-order processes with virtual intermediate states. The compound matrix element for the indirect optical transition has the standard form

$$M_{ns'k' \leftarrow nsk} = \sum_{\nu} \left(\frac{V_{ns'k',\,\nu k}\, R_{\nu k, nsk}}{E_{\nu k} - E_{nk} - \hbar\omega} + \frac{R_{ns'k',\,\nu k'}\, V_{\nu k', nsk}}{E_{\nu k'} - E_{nk}} \right) , \tag{1}$$

where $E_{n,k}$, $E_{n,k'}$ and E_{ν} are the electron energies in the initial $|n, s, \boldsymbol{k}\rangle$, final $|n, s', \boldsymbol{k}'\rangle$ and intermediate $|\nu\rangle$ states, s is the spin index, $\boldsymbol{k}$ is the electron wavevector, R is the electron-photon matrix element, V denotes the matrix element of interaction which allows the momentum transfer, e.g. scattering from impurities or phonon-assisted scattering. In the latter case the photon energy $\hbar\omega$ is assumed to exceed the energy of an involved phonon.

The most probable processes are the transitions with intermediate states in the same subband (Fig. 1). This is the channel that determines the light absorption. However such transitions conserve the electron spin and, hence, *do not* contribute to the optical orientation.

In order to obtain the spin orientation of electron gas under intrasubband optical transitions one should take into account the virtual processes with intermediate states in the valence band, namely in the heavy, light and spin-split hole subbands. We assume that the carriers occupy the lowest electron subband $e1$. Then in the case of the flat QW with infinite barriers, the interband optical transitions between the $e1$ and ν states are allowed only for the hole subbands $\nu = hh1, lh1$ and $so1$. Fig. 2 demonstrates schematically the spin orientation under the σ^+ normal-incidence excitation. In this case only the light and spin-split hole subbands contribute to the optical orientation. Because of the selection rules for interband matrix element, the electron transitions with the spin reversal $|e1, -1/2\rangle \to |e1, +1/2\rangle$

occur via the intermediate states $|lh1, \pm 1/2\rangle$ and $|so1, \pm 1/2\rangle$, while the inverse processes $|e1, +1/2\rangle \to |e1, -1/2\rangle$ are forbidden. While examining the optical orientation under oblique incidence, the heavy hole subband should also be taken into account as an intermediate state.

We consider the conduction electrons to form a nondegenerate 2D gas at the temperature T or a degenerate 2D gas with the Fermi energy ε_F, the interaction V to describe the electron scattering by bulk acoustic phonons. Then an expression for the spin generation rate at $\hbar\omega \gg k_B T$ or ε_F (k_B is Boltzmann's constant) has the form

$$\dot{\boldsymbol{S}} = \frac{1}{6} \frac{\Xi_{cv}^2}{\Xi_c^2} \frac{\Delta_{so}^2}{E_g(E_g + \Delta_{so})(3E_g + 2\Delta_{so})} \left[\boldsymbol{o}_\parallel + \frac{a}{3} \sqrt{\frac{2m^*\omega}{\hbar}} \boldsymbol{o}_z \right] \eta \, I_0 \, P_{circ} \, . \tag{2}$$

Here Ξ_{cv} and Ξ_c denote the interband and intraband deformation potential constants, Δ_{so} and E_g stand for the energies of the spin-splitting and the band gap, a is the width of the quantum well, m^* is the electron effective mass, I_0 and P_{circ} are the light intensity and the degree of circularly polarization inside the sample, $\boldsymbol{o}_\parallel$ and $\boldsymbol{o}_z$ are the in-plane and z components of the unit vector $\boldsymbol{o}$ in the light propagation direction. The factor η in Eq. (2) is the fraction of the light energy flux absorbed in the QW under phonon-assisted intrasubband optical transitions calculated for intermediate states in the same conduction subband, it is given by

$$\eta = \frac{3\pi\alpha}{n_\omega} \left(\frac{\Xi_c}{\hbar\omega} \right)^2 \frac{k_B T}{\rho a v_s^2} N_e \, , \tag{3}$$

where α and n_ω are the fine structure constant ($\approx 1/137$) and the refraction index of the medium, ρ is the crystal density, v_s is the sound velocity, and N_e is the 2D carrier concentration.

An estimation for typical GaAs/AlGaAs structures shows that, at the comparable light intensities, the spin generation rate under intrasubband phonon-assisted optical transitions is by a factor of $10^{-4} \div 10^{-5}$ smaller than that under interband excitation. However, consideration of other mechanisms of electron scattering, e.g. by impurity-assisted coupling, can essentially increase this ratio.

III. SPIN RELAXATION MECHANISM INDUCED BY INTERBAND SCATTERING

Besides the monopolar optical orientation, the virtual interband scattering described by the constant Ξ_{cv} can lead to a short-range mechanism of spin relaxation of the 2D electron gas. Microscopically this mechanism is connected with the $\boldsymbol{kp}$-induced admixture of the valence band states, Γ_8 and Γ_7, into the wave function of the conduction band Γ_6 and the phonon- or defect-assisted interband coupling of these states. For bulk semiconductors this short-range Elliot-Yafet mechanism of electron spin relaxation was considered by Pikus and Titkov (see [1], ch. 3).

The spin relaxation time due to the mechanism under consideration can be calculated using the spin-flip matrix element (1) where ν are the valence band states $\nu = hh1, lh1$ and $so1$ and, in the matrix element $R_{\nu k, nsk} = -(e/cm_0)\boldsymbol{A}\boldsymbol{p}_{\nu,ns}$, the vector $(-e/c)\boldsymbol{A}$ is replaced by the in-plane momentum $\hbar\boldsymbol{k}$. Here e is the electron charge, c is the light velocity in vacuum and $\boldsymbol{A}$ is the amplitude of the vector potential of the electro-magnetic wave.

Assuming the interband coupling V to be caused by scattering on bulk acoustic phonons one can derive the relaxation rates for the in-plane and z electron spin components which, after the averaging over the Boltzmann distribution, take the form

$$\frac{1}{\tau_{s\parallel}} = \frac{1}{6} \frac{\Xi_{cv}^2}{\Xi_c^2} \frac{\Delta_{so}^2 \, k_B T}{E_g(E_g + \Delta_{so})(3E_g + 2\Delta_{so})} \frac{1}{\tau_p} \, , \tag{4}$$

$$\frac{1}{\tau_{sz}} = \frac{2\sqrt{\pi} a}{3} \sqrt{\frac{2m^*}{\hbar^2} k_B T} \frac{1}{\tau_{s\parallel}} \, , \tag{5}$$

where the momentum relaxation time determined by the acoustic phonon-assisted scattering is given by

$$\frac{1}{\tau_p} = \frac{3}{2} \frac{m^* \, \Xi_c^2}{\rho a v_s^2 \hbar^3} k_B T \, . \tag{6}$$

One can see that, in case of the scattering by acoustic phonons, the spin relaxation of the 2D electron gas governed by the short-range Elliot-Yafet mechanism is very anisotropic, $\tau_{s\parallel} \ll \tau_{sz}$.

Acknowledgements

This work was supported by the Russian Ministry of Science, the RFFI (projects 00-02-16997 and 01-02-17528), the INTAS (project 99-00015), and by the Science Programme of the Presidium of RAS "Quantum low-dimensional structures".

---

[1] *Optical orientation*, eds. F. Meier and B.P. Zakharchenya, North Holland, 1984 [Russian edition: Leningrad, Nauka, 1989].

[2] A.M. Danishevskii, E.L. Ivchenko, S.F. Kochegarov, V.K. Subashiev, Sov. Phys. Solid State **27**, 439 (1985) [*Fiz. Tverd. Tela* **27**, 710 (1985)].

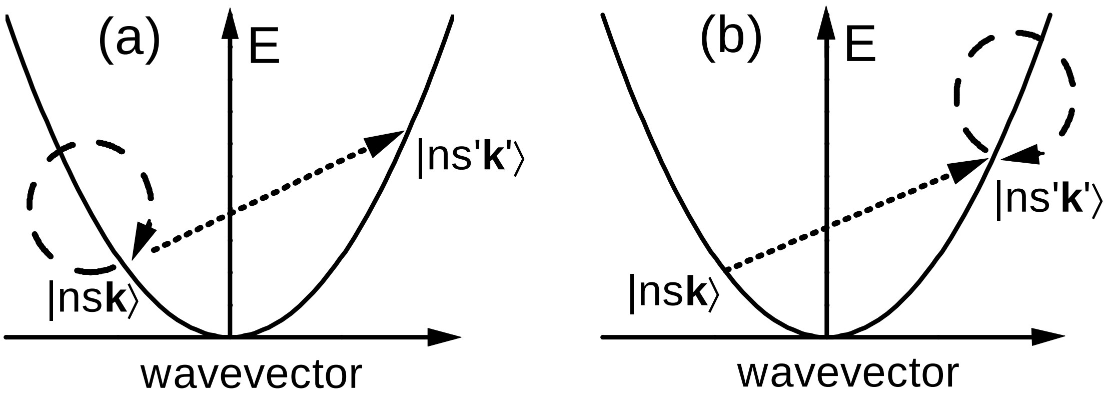

Fig.1 The schematic representation of indirect intrasubband optical transitions with intermediate states in the same subband. Dashed and dotted curves indicate the electron-photon interaction and the electron momentum scattering. Figures (a) and (b) account for the first and the second terms in Eq.(1).

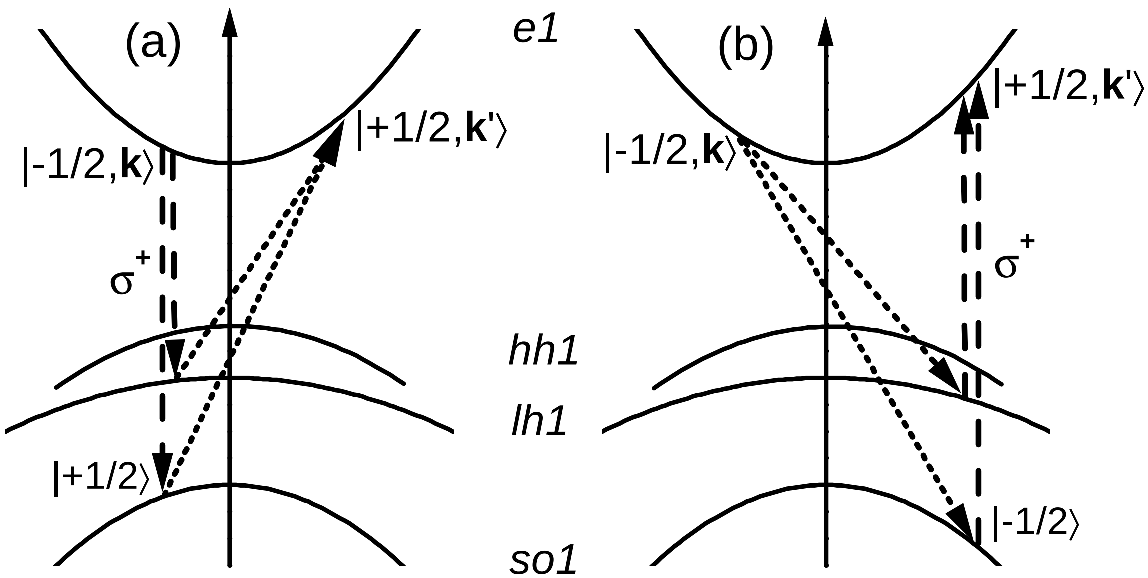

Fig.2 The sketch of indirect intrasubband optical transitions with intermediate states in the valence band.